Simulating Heavy Neutral Leptons with General Couplings at Collider and Fixed Target Experiments

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2405.07330

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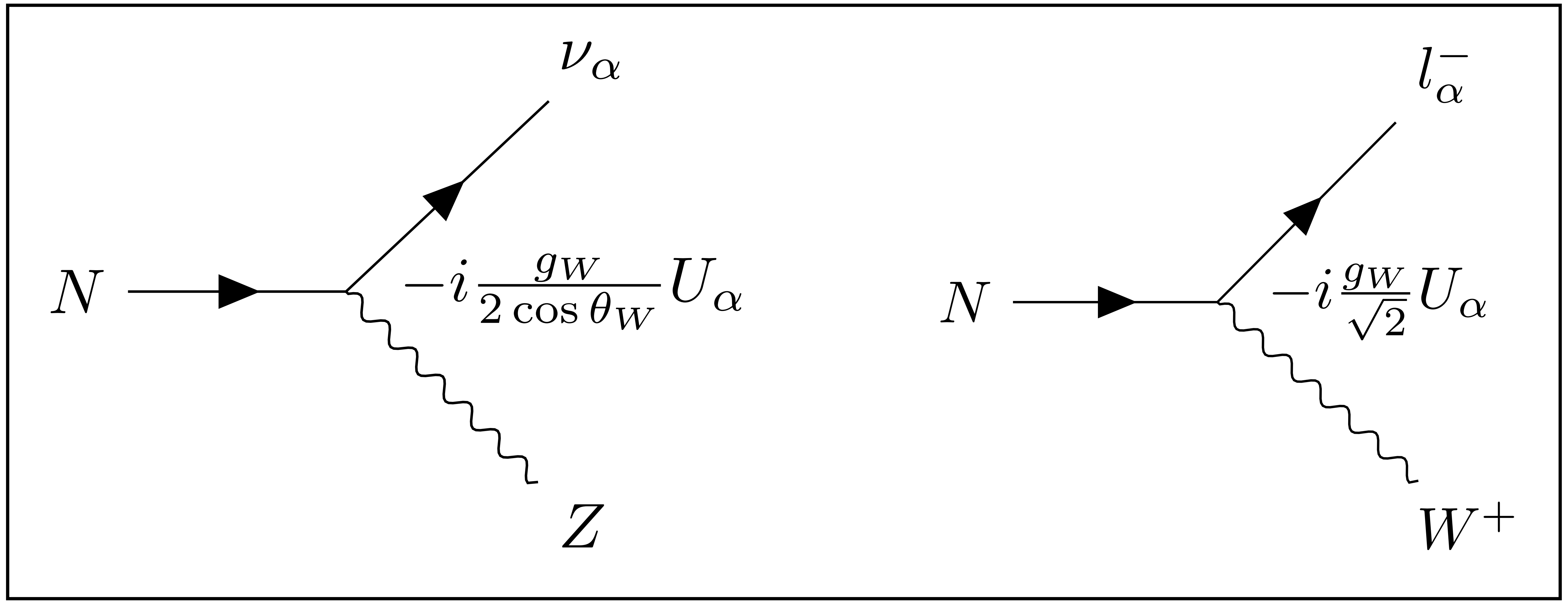
Heavy Neutral Leptons (HNLs): a brief review

- Heavy Neutral Leptons, or right-handed/sterile neutrinos, are an extension of the SM with singlet fermions under G_{SM}
- EWSB generally leads to a non-diagonal neutrino mass matrix M_ν, which after diagonalization results in eigenstates with non-trivial mixings with active neutrino flavors
- Through mixing, HNLs pick up suppressed neutral current (NC) and charged-current (CC) interactions with the Z and W bosons, respectively

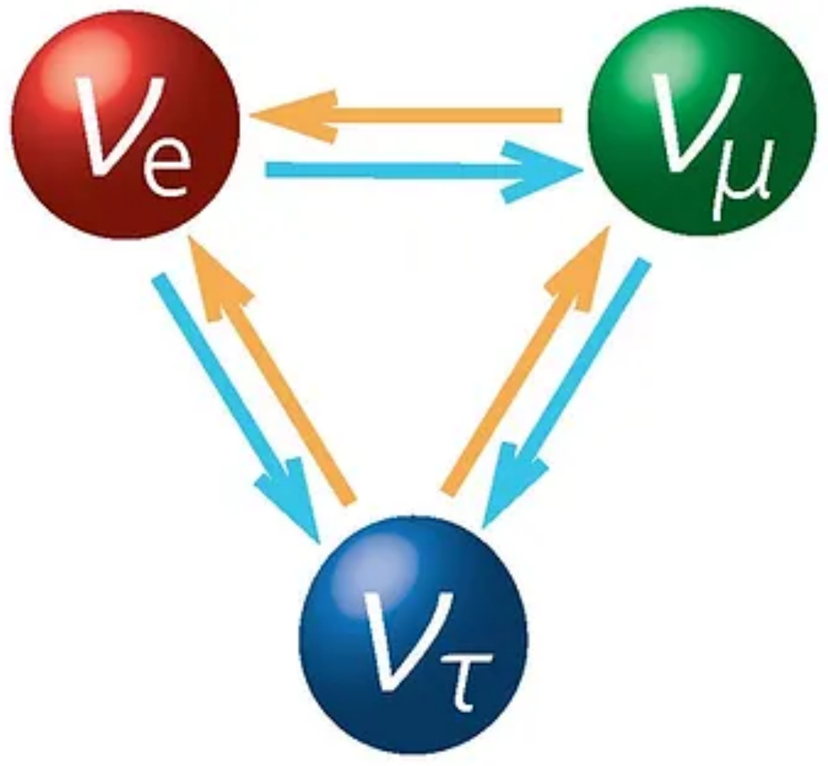
$$\mathscr{L} \supset -\sum_{\alpha i} Y_{\alpha i}\overline{L}_\alpha \tilde{\phi} N_i' - \sum_{ij} m_{ij}\overline{N_i'^c} N_j' - \sum_{\alpha\beta} \frac{C_5^{\alpha\beta}}{\Lambda}\overline{L}_\alpha \tilde{\phi}\tilde{\phi}^T L_\beta^c + \text{h.c.}$$

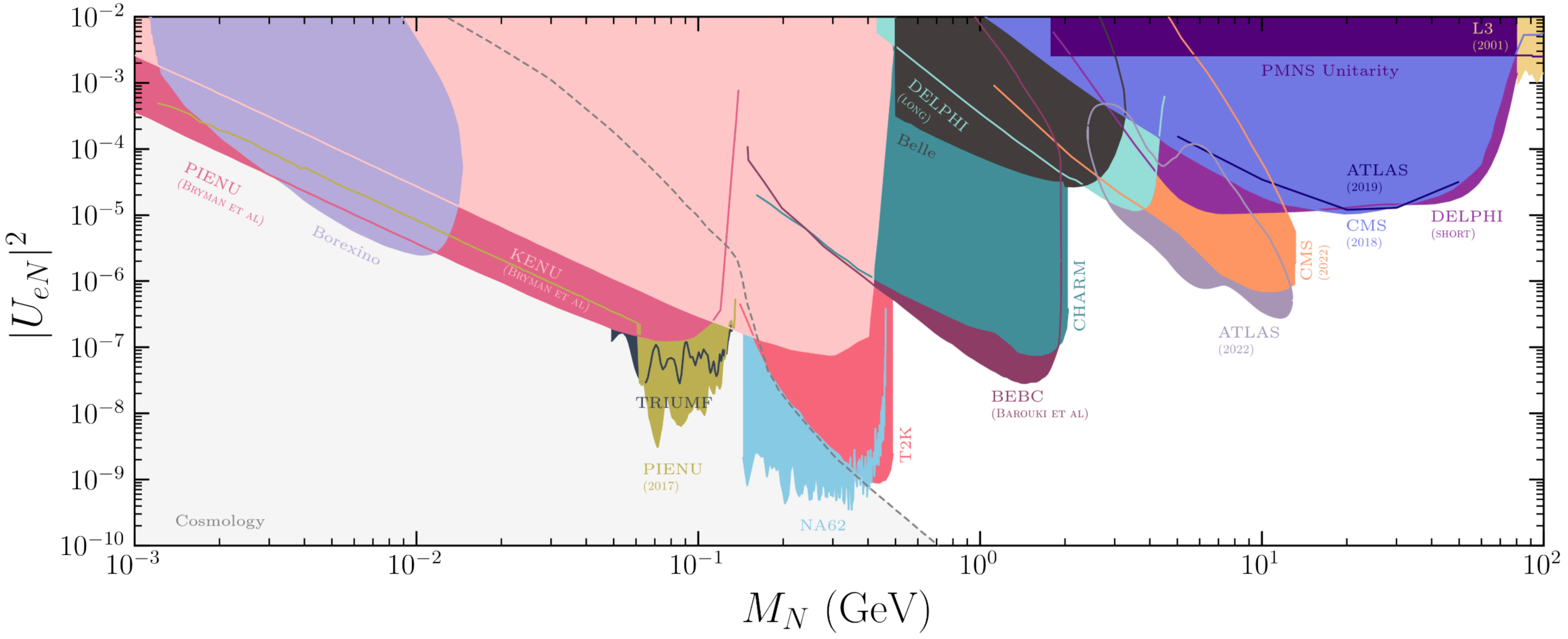
$$M_\nu = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix} \rightarrow \nu_\alpha = \sum_{i=1}^{3} V_{\alpha i}\nu_i + U_\alpha N^c$$



Motivations and Benchmarks

- Motivations:
  - Neutrino Oscillations
  - Baryon Asymmetry
  - Dark Matter
- HNLs in the MeV to GeV range (this work) have been studied as early as the 1970's:
  - Bjorken & Llewellyn Smith, [Phys. Rev. D](#) (1973)
  - Shrock, [Phys. Rev. D](#) (1974)





[Fernández-Martínez et al. 2304.06772]

- Singly-coupled HNL models have served as well-defined simple benchmarks for experimental searches (Physics Beyond Colliders Working Group [1901.09966](#))
- However, models with more general mixed couplings are well motivated and appear naturally in many SM extensions! (e.g. models with flavor symmetries)
- In our work, we consider as examples the recently proposed benchmarks (Drewes, Klarić, & López-Pavón [2207.02742](#)):
  - $U_\mu = U_\tau \neq 0, \quad U_e = 0$
  - $U_e = U_\mu = U_\tau \neq 0$ (Presented in this talk)

HNLCalc

A fast, flexible, and comprehensive python package for calculating Majorana HNL production and decay rates with arbitrary couplings

- Allows user to specify an arbitrary coupling ratio, $U_e : U_\mu : U_\tau$ and normalization $\epsilon^2 = |U_e|^2 + |U_\mu|^2 + |U_\tau|^2$.
- Features:
  - Calculates HNL production branching fractions, $B(A \to N \ldots)$ and provides differential branching fractions for use in MC event generators
  - Calculates HNL decay branching fractions, $B(N \to A \ldots)$ and decay lengths, $c\tau$
  - Includes plotting tools for visualization

README

HNLCalc: Heavy Neutral Lepton Calculator

By Alec Hewitt and Daniel La Rocco

Introduction

We present the package, **HNLCalc**, a fast and flexible tool which can be used to compute production rates, decay rates, and lifetimes for Heavy Neutral Leptons, a.k.a. Sterile Neutrinos, with arbitrary couplings to the electron, muon, and tau neutrinos. We have implemented over 150 produciton modes and over 100 decay modes, resulting in a comprehensive tool that can be used to study HNL phenomenology for masses up to 10 GeV.

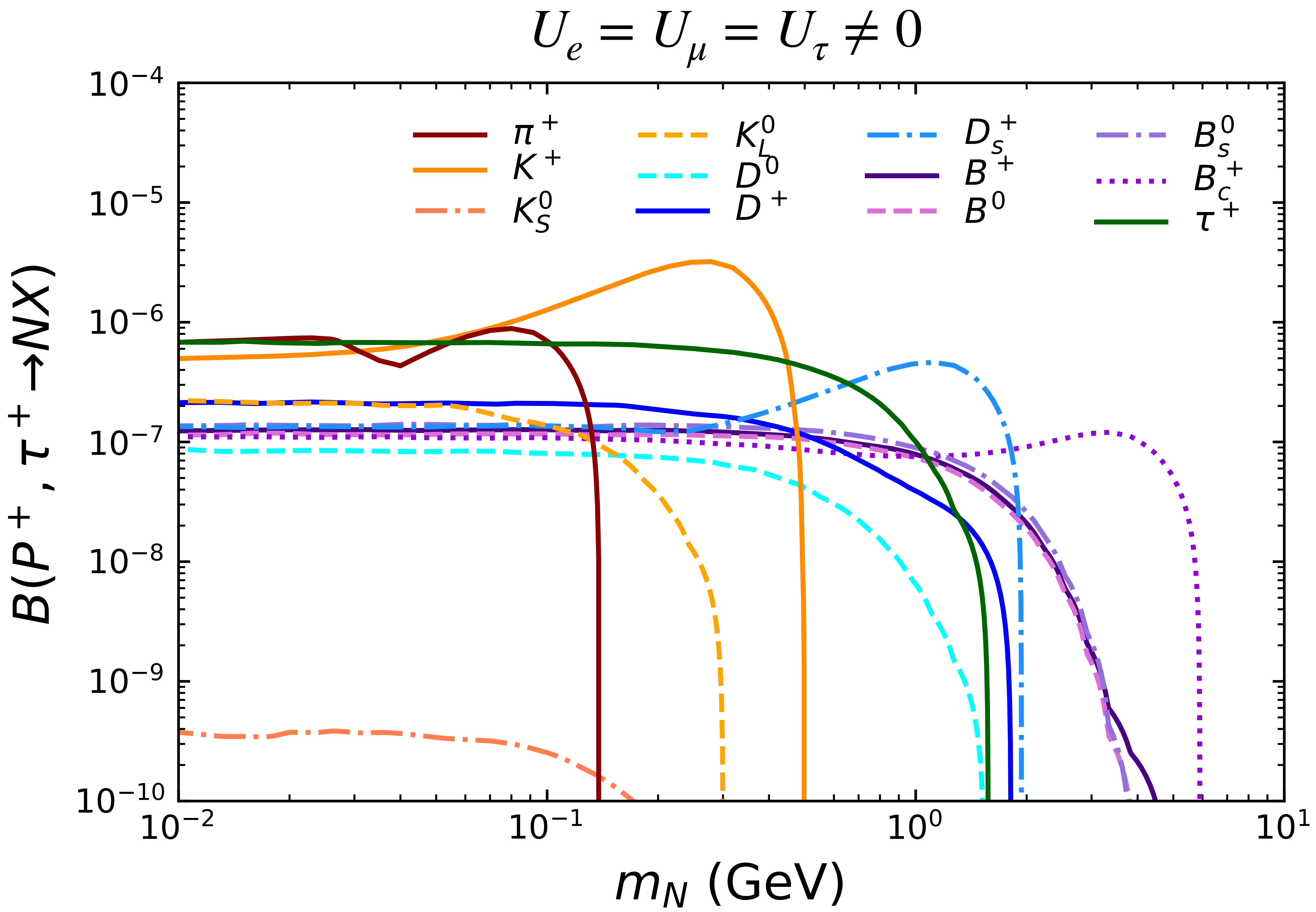
Paper

Our primary publication Simulating Heavy Neutral Leptons with General Couplings at Collider and Fixed Target Experiments provides an overview of the production and decay channels that are implemented in the package. Additionally, it showcases an example of how HNLCalc can be used, where we have used HNLCalc to extend the **FORESEE** (FORward Experiment SEnsitivity Estimator) package to study HNL phenomenology and sensitivity for forward physics experiments.

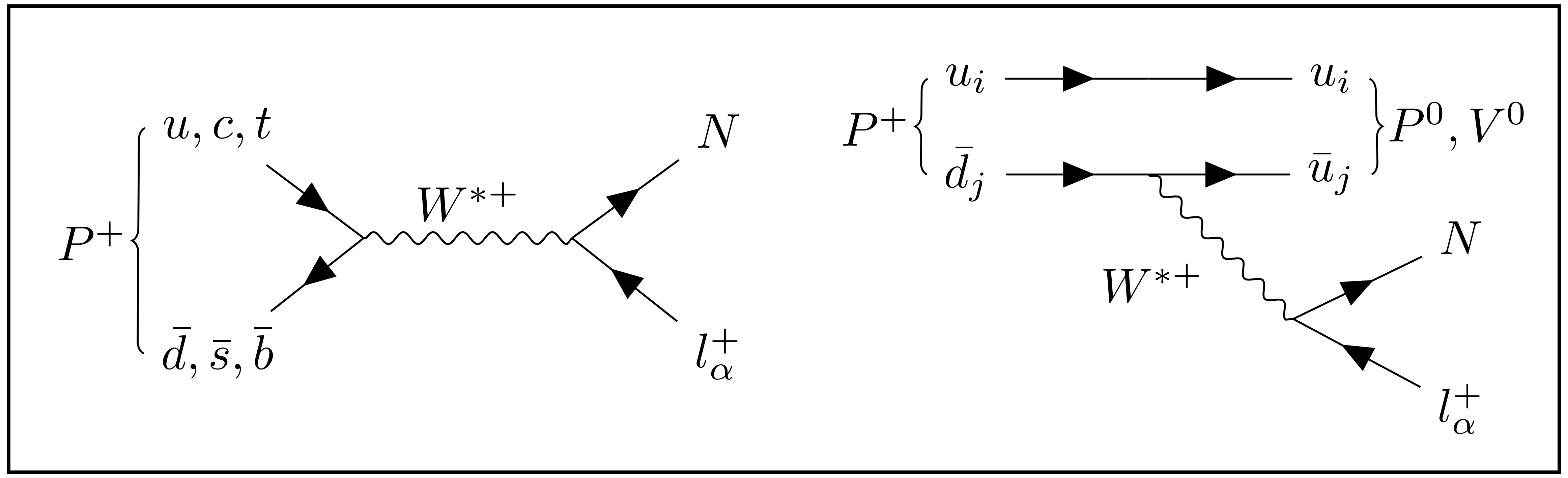
Available on GitHub

HNL Production

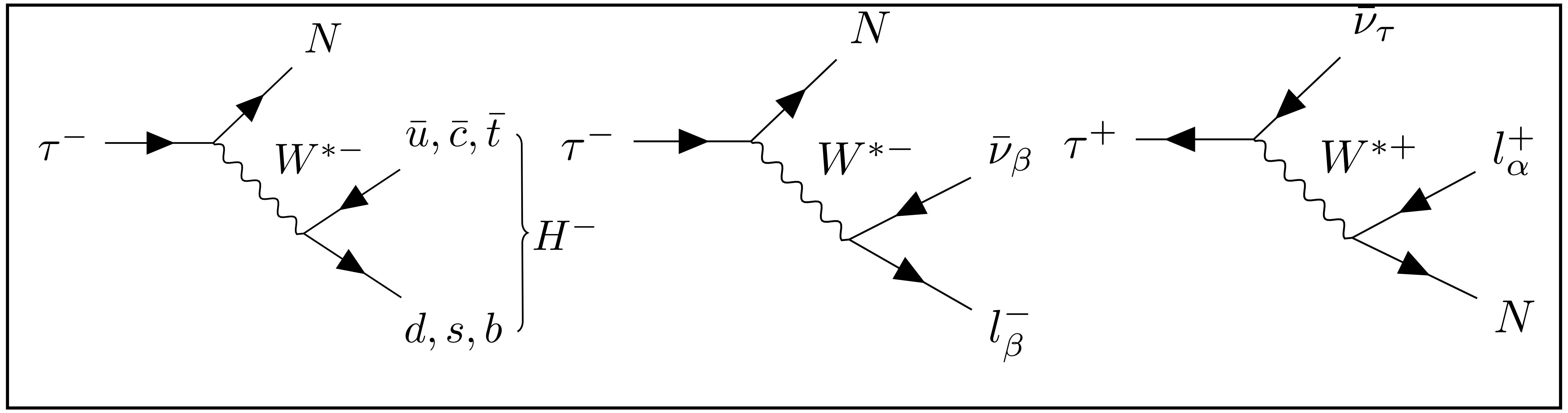
- HNLCalc includes HNL production from the decay of pseudoscalar mesons and tau leptons
- For HNLs in the mass range 100 MeV to 10 GeV, these are the dominant production mechanisms



Pseudoscalar



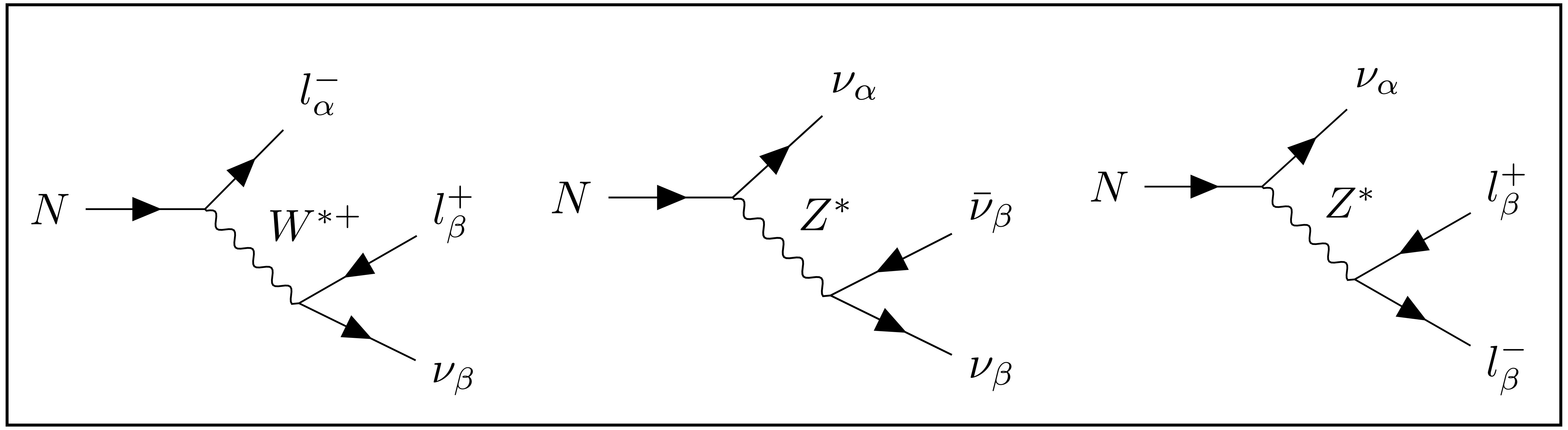
Tau



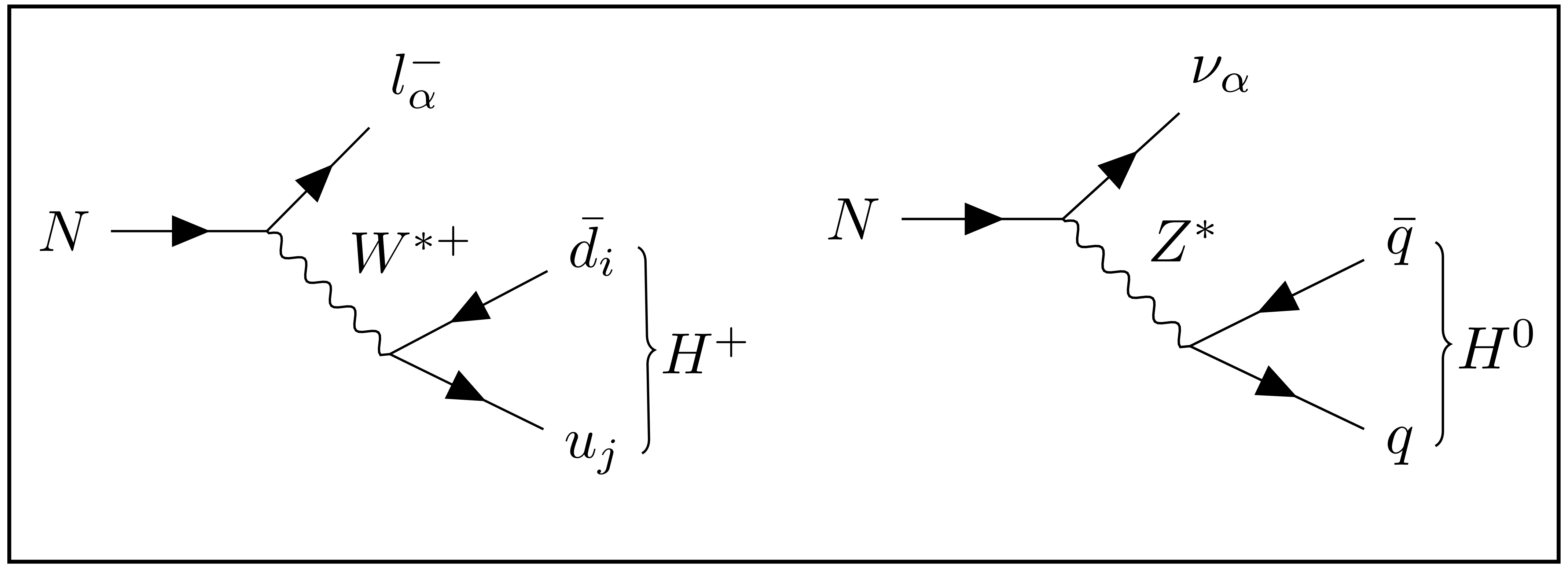
HNL Decay

- HNLs can decay at tree-level into leptonic or hadronic final states through virtual W and Z exchange
- In order to properly simulate detector response, one must accurately represent the final states
    - i.e. $N \to \nu\rho \to \nu\pi^+\pi^-$ vs $N \to \nu\pi^0 \to \nu\gamma\gamma$
    - Quark-level final states are insufficient!
- However, for $m_N > 1$ GeV, decays into single hadronic states are insufficient for modeling the total HNL decay width, since in this regime multi-meson final states become relevant
- We adopt the approach in Bondarenko et al. (1805.08567) for calculating the total hadronic widhth:
    - For $m_N < 1$ GeV: Single meson decays
    - For $m_N > 1$ GeV: Quark-level decays + QCD Correction

Leptonic



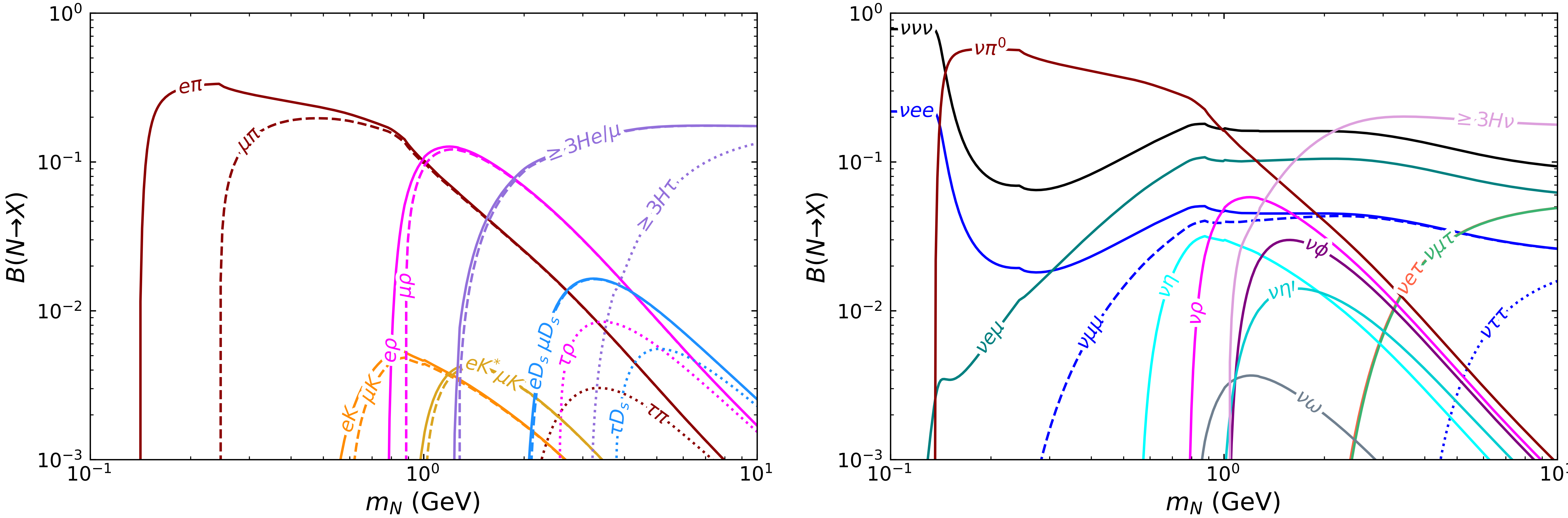
Hadronic



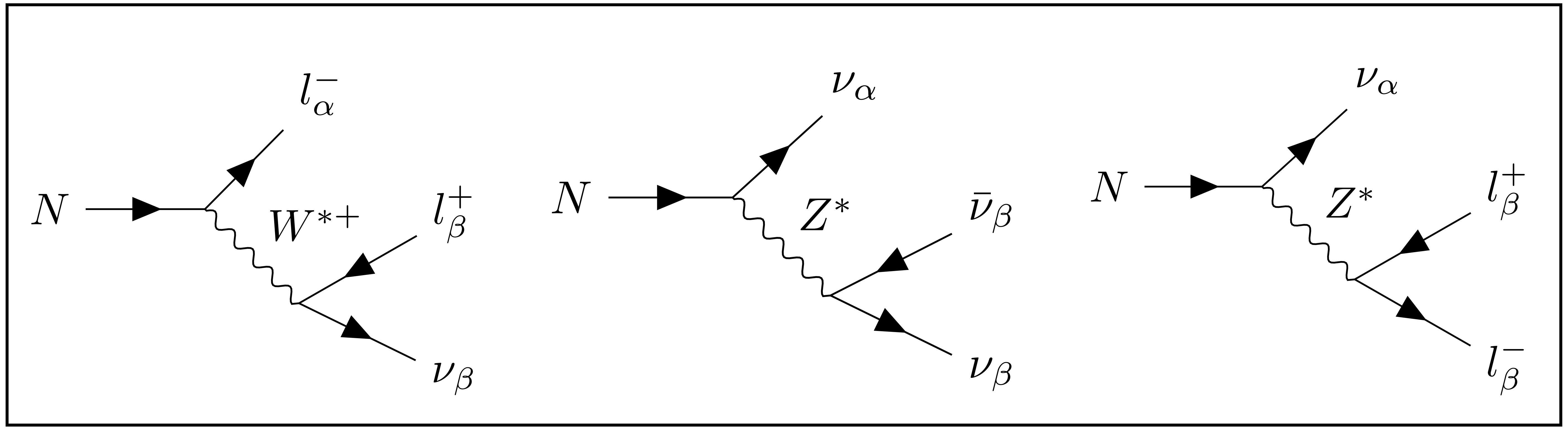
HNL Decay

- HNLCalc includes HNL decays into leptonic and hadronic final states
- HNLs with masses ~130 MeV - 1 GeV decay dominantly into $\pi^{\pm}/\pi^{0}$
- Above 1 GeV, multi-hadron and leptonic decays become most relevant

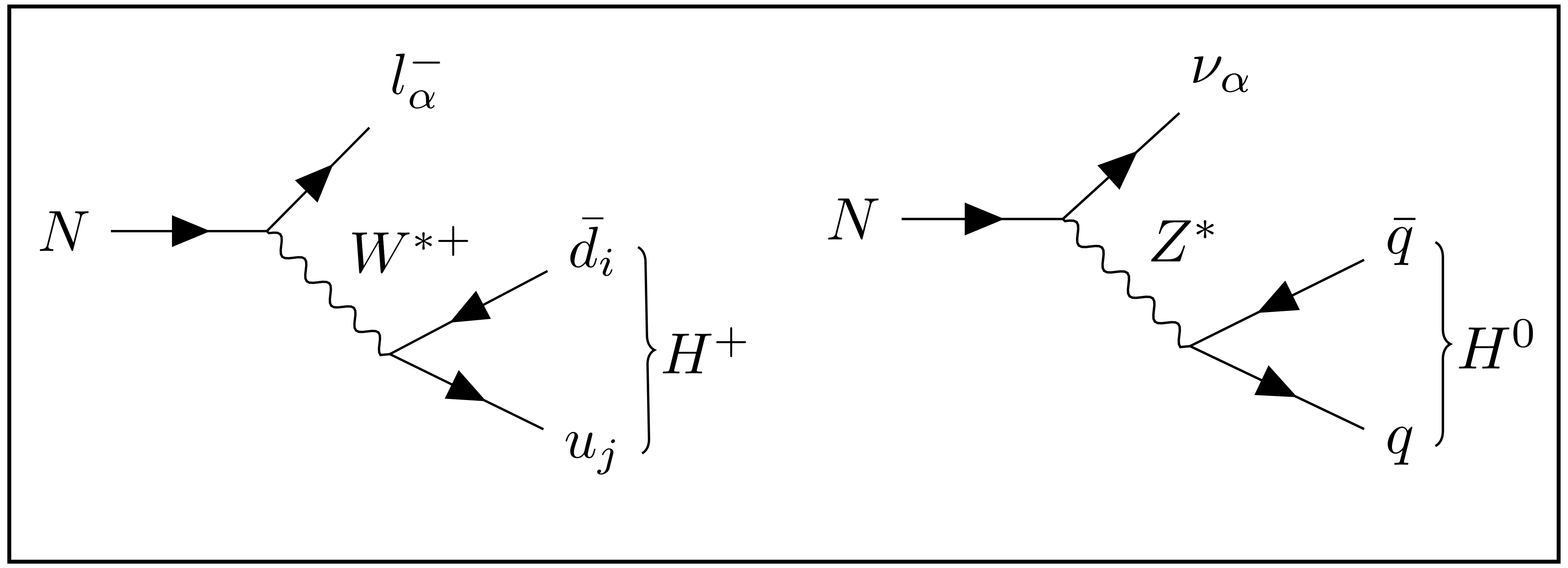
$U_e = U_\mu = U_\tau \neq 0$



Leptonic



Hadronic



HNLCalc Summary

HNL Decay Modes							
$\nu\, l^+ l^-$	Fig. 3 (a)	$\nu_l e^+ e^-$	$\nu_l \mu^+ \mu^-$	$\nu_l \tau^+ \tau^-$			
$l^\pm\, \nu_{l'} l'^\mp$	Fig. 3 (b)	$l^\pm \nu_e e^\mp$	$l^\pm \nu_\mu \mu^\mp$	$l^\pm \nu_\tau \tau^\mp$			
$\nu_l\, \overline{\nu} \nu$	Fig. 3 (c)	$\nu_l \bar{\nu}_e \nu_e$	$\nu_l \bar{\nu}_\mu \nu_\mu$	$\nu_l \bar{\nu}_\tau \nu_\tau$			
$\nu_l\, H^0$	Fig. 3 (d)	$\nu_l \pi^0$	$\nu_l \eta$	$\nu_l \eta'$	$\nu_l \rho^0$	$\nu_l \omega$	$\nu_l \phi$
$l^\pm\, H^\mp$	Fig. 3 (e)	$l^\pm \pi^\mp$	$l^\pm K^\mp$	$l^\pm D^\mp$	$l^\pm D_s^\mp$	$l^\pm \rho^\mp$	$l^\pm K^{*\mp}$
$\nu_l\, q\bar{q}$	Fig. 3 (d)	$\nu_l u\bar{u}$	$\nu_l d\bar{d}$	$\nu_l s\bar{s}$	$\nu_l c\bar{c}$	$\nu_l b\bar{b}$	
$l^\pm\, u\bar{d}'$	Fig. 3 (e)	$l^- u\bar{d}$	$l^- u\bar{s}$	$l^- u\bar{b}$	$l^+ \bar{u}d$	$l^+ \bar{u}s$	$l^+ \bar{u}b$
		$l^- c\bar{d}$	$l^- c\bar{s}$	$l^- c\bar{b}$	$l^+ \bar{c}d$	$l^+ \bar{c}s$	$l^+ \bar{c}b$

HNL Production Processes							
$P \to lN$	Fig. 1 (a)	$\pi^+ \to l^+ N$	$K^+ \to l^+ N$	$D^+ \to l^+ N$	$D_s^+ \to l^+ N$	$B^+ \to l^+ N$	$B_c^+ \to l^+ N$
$P \to P' lN$	Fig. 1 (b)	$K^+ \to \pi^0 l^+ N$	$K_S \to \pi^+ l^- N$	$K_L \to \pi^+ l^- N$	$D^0 \to K^- l^+ N$	$\bar{D}^0 \to \pi^+ l^- N$	$D^+ \to \pi^0 l^+ N$
		$D^+ \to \eta l^+ N$	$D^+ \to \eta' l^+ N$	$D^+ \to \bar{K}^0 l^+ N$	$D_s^+ \to \bar{K}^0 l^+ N$	$D_s^+ \to \eta l^+ N$	$D_s^+ \to \eta' l^+ N$
		$B^+ \to \pi^0 l^+ N$	$B^+ \to \eta l^+ N$	$B^+ \to \eta' l^+ N$	$B^+ \to \bar{D}^0 l^+ N$	$B^0 \to \pi^- l^+ N$	$B^0 \to D^- l^+ N$
		$B_s^0 \to K^- l^+ N$	$B_s^0 \to D_s^- l^+ N$	$B_c^+ \to D^0 l^+ N$	$B_c^+ \to \eta_c l^+ N$	$B_c^+ \to B^0 l^+ N$	$B_c^+ \to B_s^0 l^+ N$
$P \to VlN$	Fig. 1 (b)	$D^0 \to \rho^- l^+ N$	$D^0 \to K^{*-} l^+ N$	$D^+ \to \rho^0 l^+ N$	$D^+ \to \omega l^+ N$	$D^+ \to \bar{K}^{*0} l^+ N$	$D_s^+ \to K^{*0} l^+ N$
		$D_s^+ \to \phi l^+ N$	$B^+ \to \rho^0 l^+ N$	$B^+ \to \omega l^+ N$	$B^+ \to \bar{D}^{*0} l^+ N$	$B^0 \to \rho^- l^+ N$	$B^0 \to D^{*-} l^+ N$
		$B_s^0 \to K^{*-} l^+ N$	$B_s^0 \to D_s^{*-} l^+ N$	$B_c^+ \to D^{*0} l^+ N$	$B_c^+ \to J/\psi\, l^+ N$	$B_c^+ \to B^{*0} l^+ N$	$B_c^+ \to B_s^{*0} l^+ N$
$\tau \to HN$	Fig. 1 (c)	$\tau^+ \to \pi^+ N$	$\tau^+ \to K^+ N$	$\tau^+ \to \rho^+ N$	$\tau^+ \to K^{*+} N$		
$\tau^+ \to l^+ \nu N$	Fig. 1 (d,e)	$\tau^+ \to l^+ \bar{\nu}_\tau N$	$\tau^+ \to l^+ \nu_l N$				

Over 150 production modes and 100 decay channels implemented!

Sources

Decay Formulae:

Coloma, Fernandez-Martinez, Gonzalez-Lopez, Hernandez-Garcia & Pavlovic 2007.03701

Bondarenko, Boyarsky, Gorbunov, & Ruchayskiy 1805.08567

Production Formulae:

Gorbunov & Shaposhnikov 0705.1729

Form Factors:

Melikhov & Stech 0001113

Decay Constants:

Faustov & Galkin 1212.3167

Ivanov, Korner, & Santorelli0007169

Chang, Li X.N., Li X.Q., Su 1805.00718

Feldmann 9907491

Application:
HNLs in FORESEE

Application: HNLs in FORESEE

- The FORward Experiment SEnsitivity Estimator (FORESEE) is a MC event generator and reach estimator used to simulate forward physics LLP searches with customizable detector geometries
- Contains a model library with various BSM Models: ALPs, Dark Photons, Dark Higgs, etc...
- In our work, we have utilized HNLCalc to extend the FORESEE model library to include HNLs
- As examples, we will use this to compute sensitivity estimates for FASER and FASER2

README | MIT license

FORESEE: FORward Experiment SEnsitivity Estimator

By Felix Kling and Sebastian Trojanowski

arXiv 2105.07077 | License MIT

Introduction

We present the numerical package **FOR**ward Experiment **SE**nsitivity **E**stimator, or **FORESEE**, that can be used to simulate the expected sensitivity reach of experiments placed in the far-forward direction from the proton-proton interaction point. We also provide a comprehensive list of validated forward spectra of various SM species.

Paper

Our main publication FORESEE: FORward Experiment SEnsitivity Estimator for the LHC and future hadron colliders provides an overview over this package. We recommend reading it first before jumping into the code.

Available on GitHub

FORESEE Models: Heavy Neutral Leptons (HNLs)

Load Libraries

```
[ ]: ...
from HNLCalc import *
```

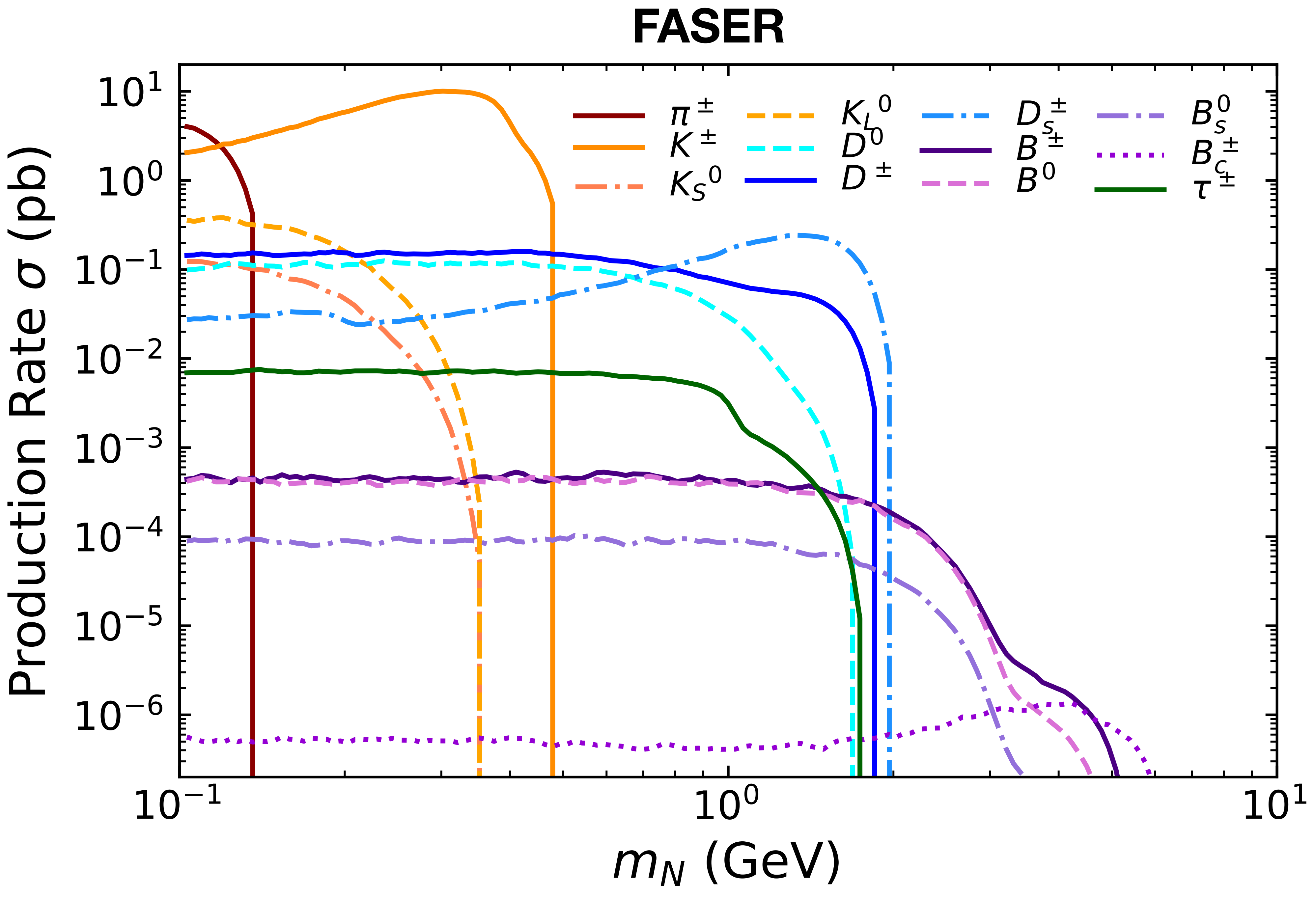
1. Specifying the Model

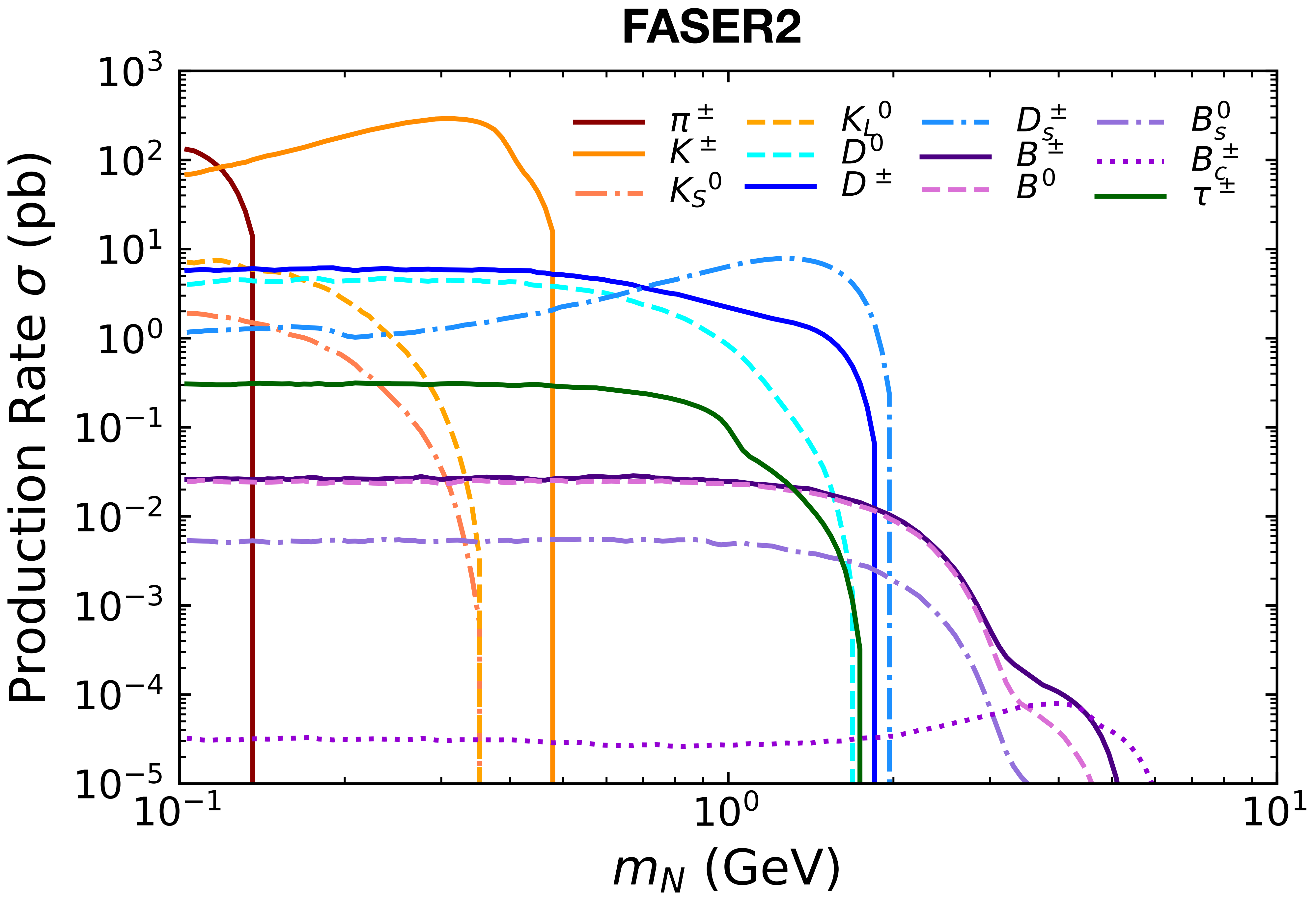
Heavy Neutral Leptons, denoted by N, are fermionic gauge singlets that can be added as an extenstion to the standard model. These HNLs mix with the SM active neutrinos, and thus pick up couplings to the SM which are suppresed by a small mixing angle, U_α for $\alpha = e, \mu, \tau$. The phenomenology of these interactions can be described by the following Lagrangian:

$$\mathcal{L} \supset -m_N \bar{N}^c N - \frac{1}{\sqrt{2}} g \sum_{\alpha=e,\mu,\tau} U_\alpha^* W_\mu^+ \overline{N^c} \gamma^\mu l_\alpha - \frac{1}{2\cos\theta_W} g \sum_{\alpha=e,\mu,\tau} U_\alpha^* Z_\mu \overline{N^c} \gamma^\mu \nu_\alpha + \text{h.c.}.$$

Hadron Production

- FORESEE generates HNL production rates through sampling of decays of parent particles, whose spectra are generated via MC event generators
- The primary source of uncertainty in HNL production rates is the modeling of the hadron fluxes
- For light hadrons (π, K), we estimate this uncertainty by considering the predictions of EPOS-LHC, QGSJET 2.04, and Sibyll 2.3d
- For heavy hadrons and taus, the uncertainty is estimated by considering predictions from POWHEG+Pythia with different choices of factorization scale

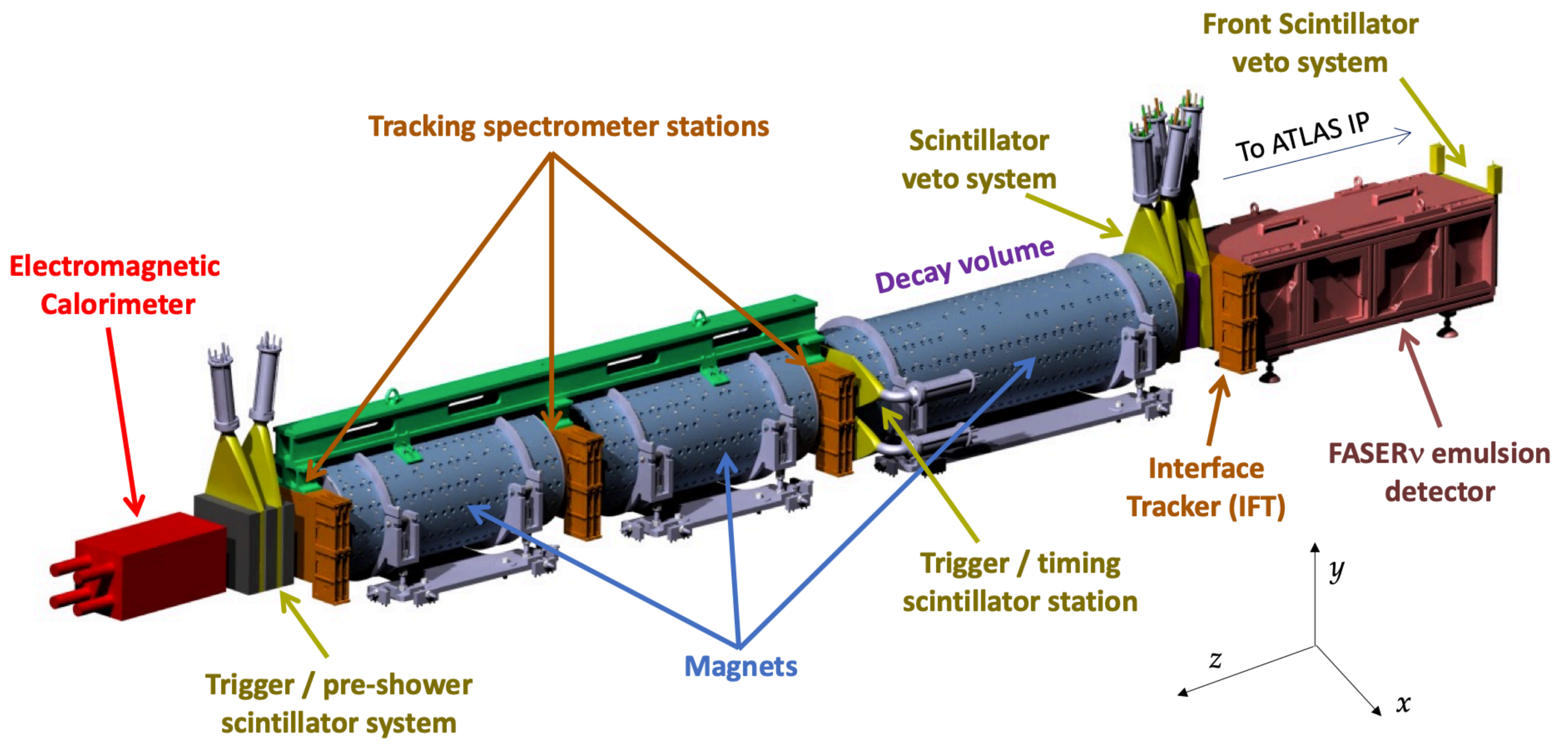




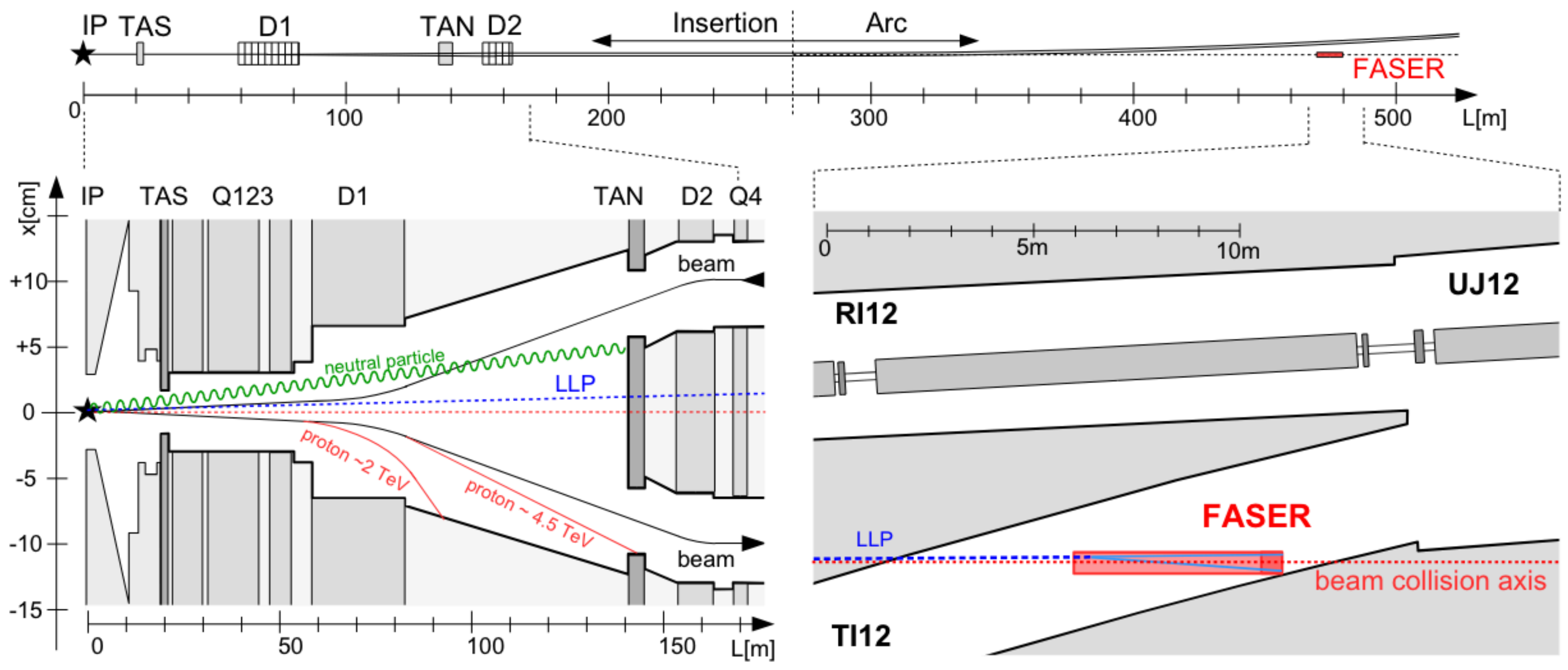
FASER

- The ForwArd Search ExpeRiment (FASER) is an experiment at the LHC designed to detect forward boosted LLPs produced at the ATLAS interaction point
- Located 480 meters down the beam axis, through 100m of rock
- Features a cylindrical decay volume with radius $R = 10$ cm and length $\Delta = 1.5$ m
- Angular coverage of $\theta \lesssim 0.2$ mrad ($\eta \gtrsim 9.2$)

FASER



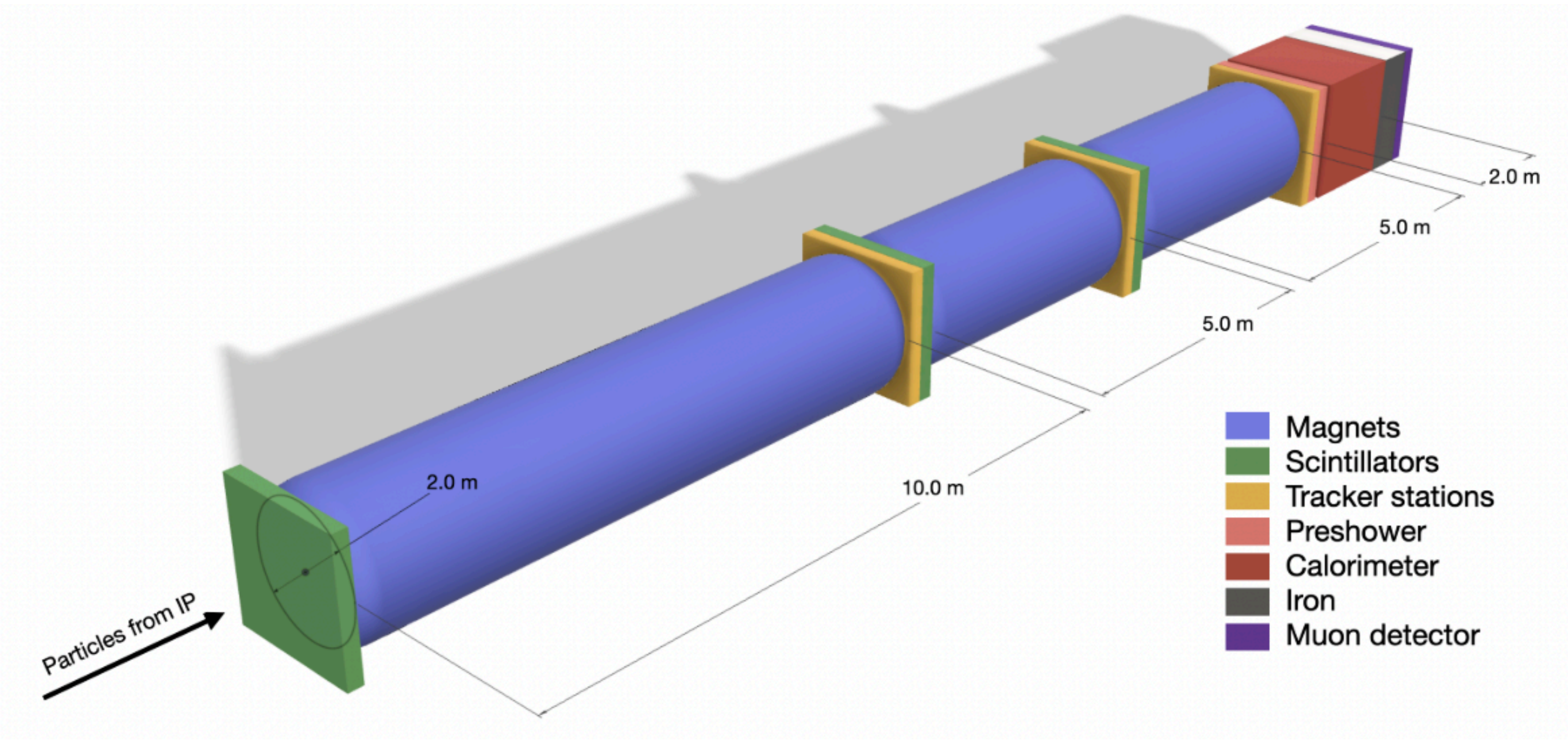
[FASER Collaboration 2207.11427]



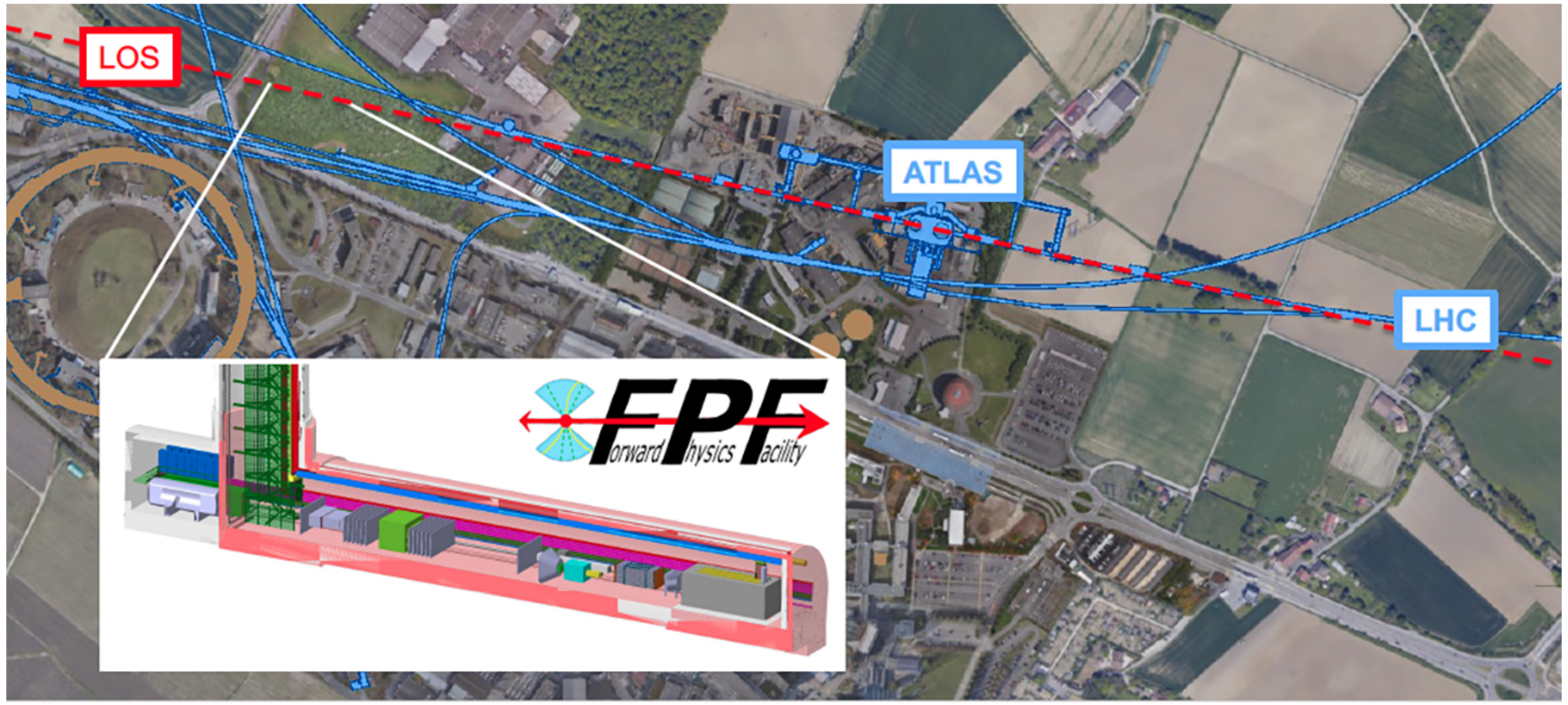
[FASER Collaboration 1811.12522]

FPF: FASER2

- The Forward Physics Facility (FPF) is a proposed underground facility to house a suite of forward physics experiments during the High-Luminosity LHC era (HL-LHC)
- FASER2 is a proposed FPF experiment with an enlarged decay volume compared to FASER, which could extend the physics reach of the FASER program significantly
- Located 650 meters down the beam axis, with a rectangular decay volume with cross-section 3 m $\times$ 1 m and length $\Delta = 10$ m.
- Angular coverage of $\theta \lesssim 2.4$ mrad $(\eta \gtrsim 6.7)$



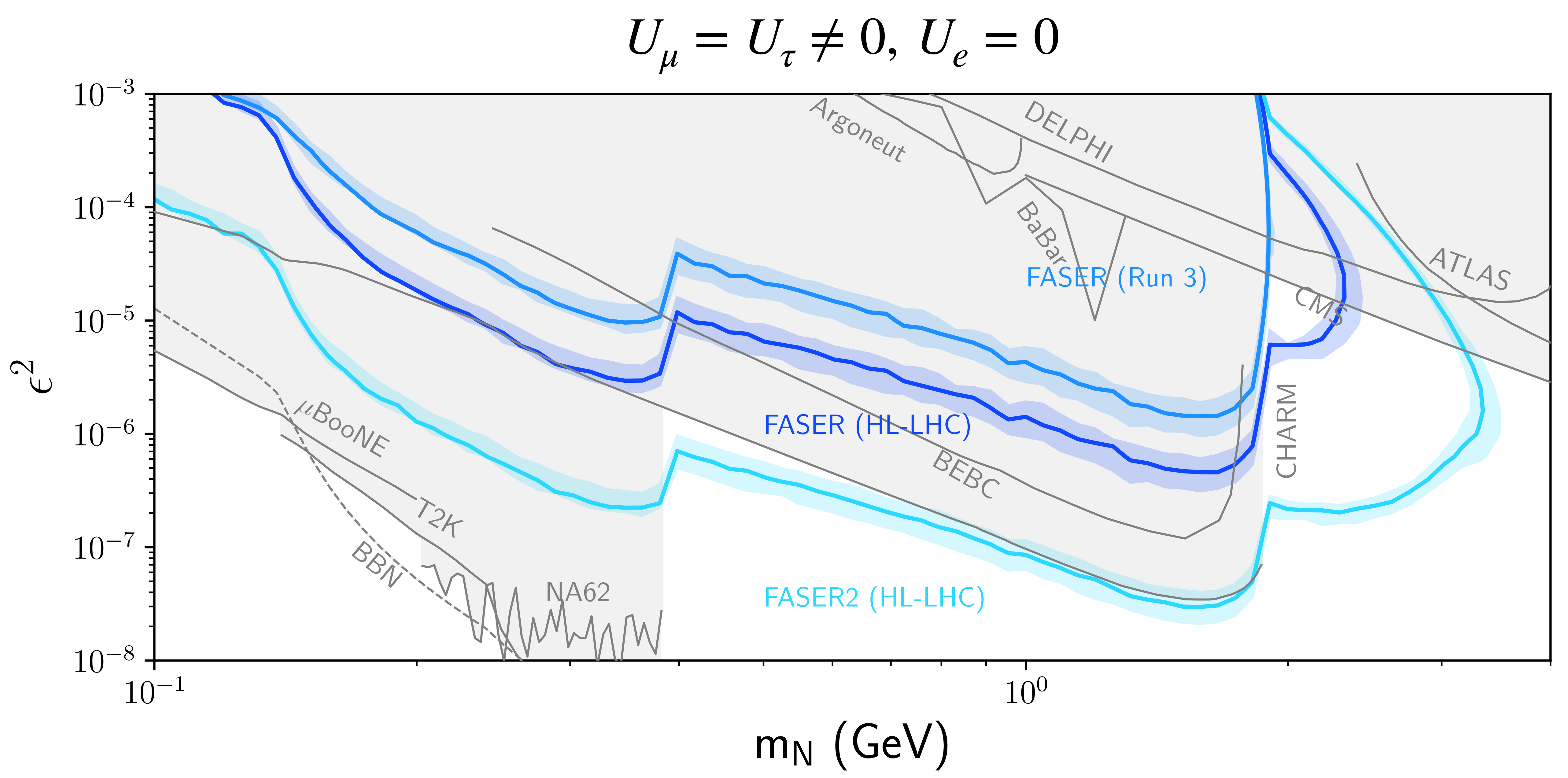
[Feng et al. 2203.05090]

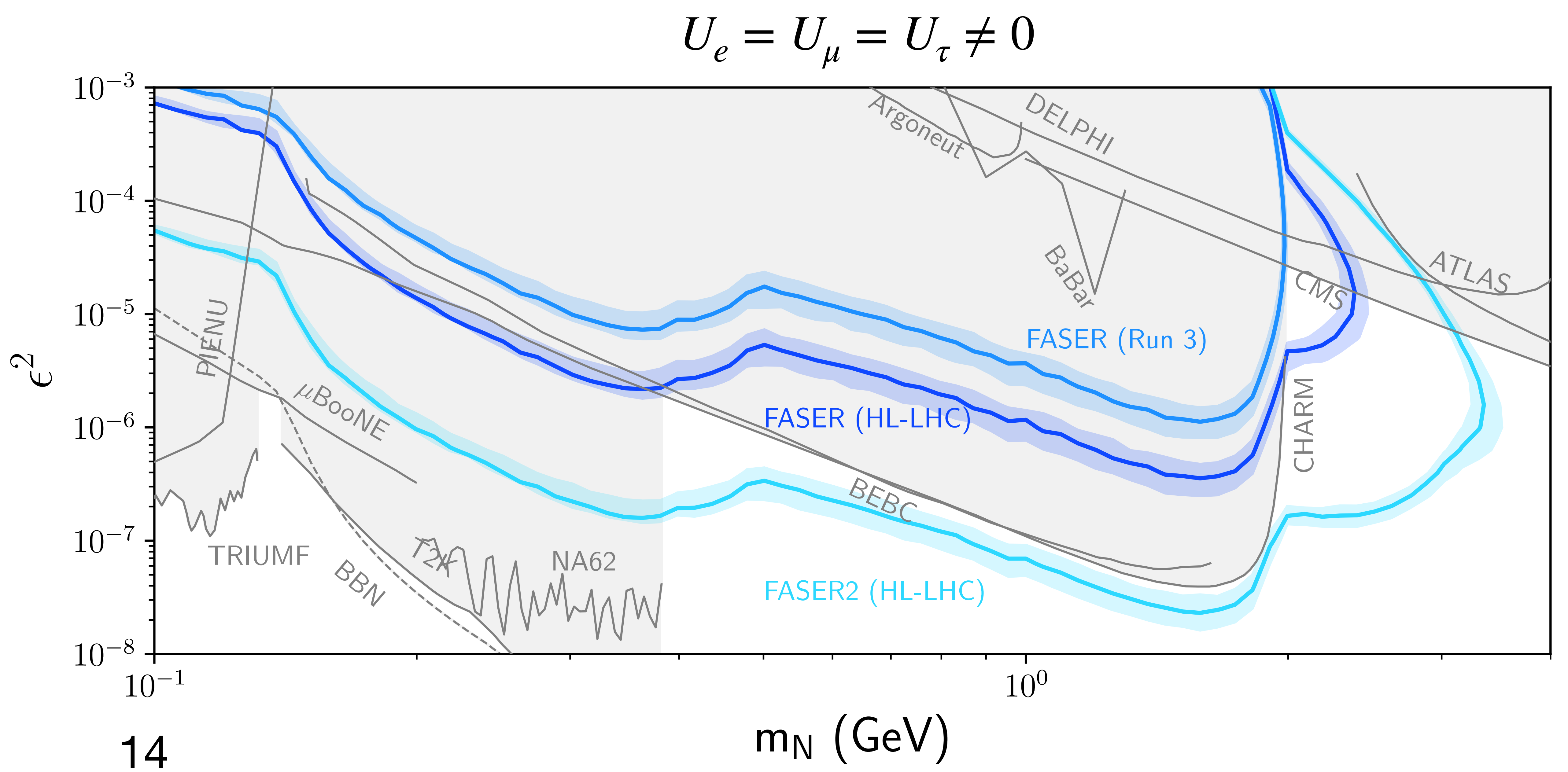


[https://fpf.web.cern.ch/]

Results: FASER Sensitivity

- We present results for FASER during Run 3 ($\mathscr{L} = 250$ fb^{-1}), and FASER/FASER2 during HL-LHC ($\mathscr{L} = 3000$ fb^{-1})
- Bounds from previous experiments are estimated from singly-coupled studies
- We find that the HL-LHC upgrade will enhance the reach of FASER/FASER2 into unconstrained parameter space, with FASER2 seeing a significant increase in sensitivity due to its larger decay volume
- Results are easily obtained for different coupling ratios using the FORESEE Module!

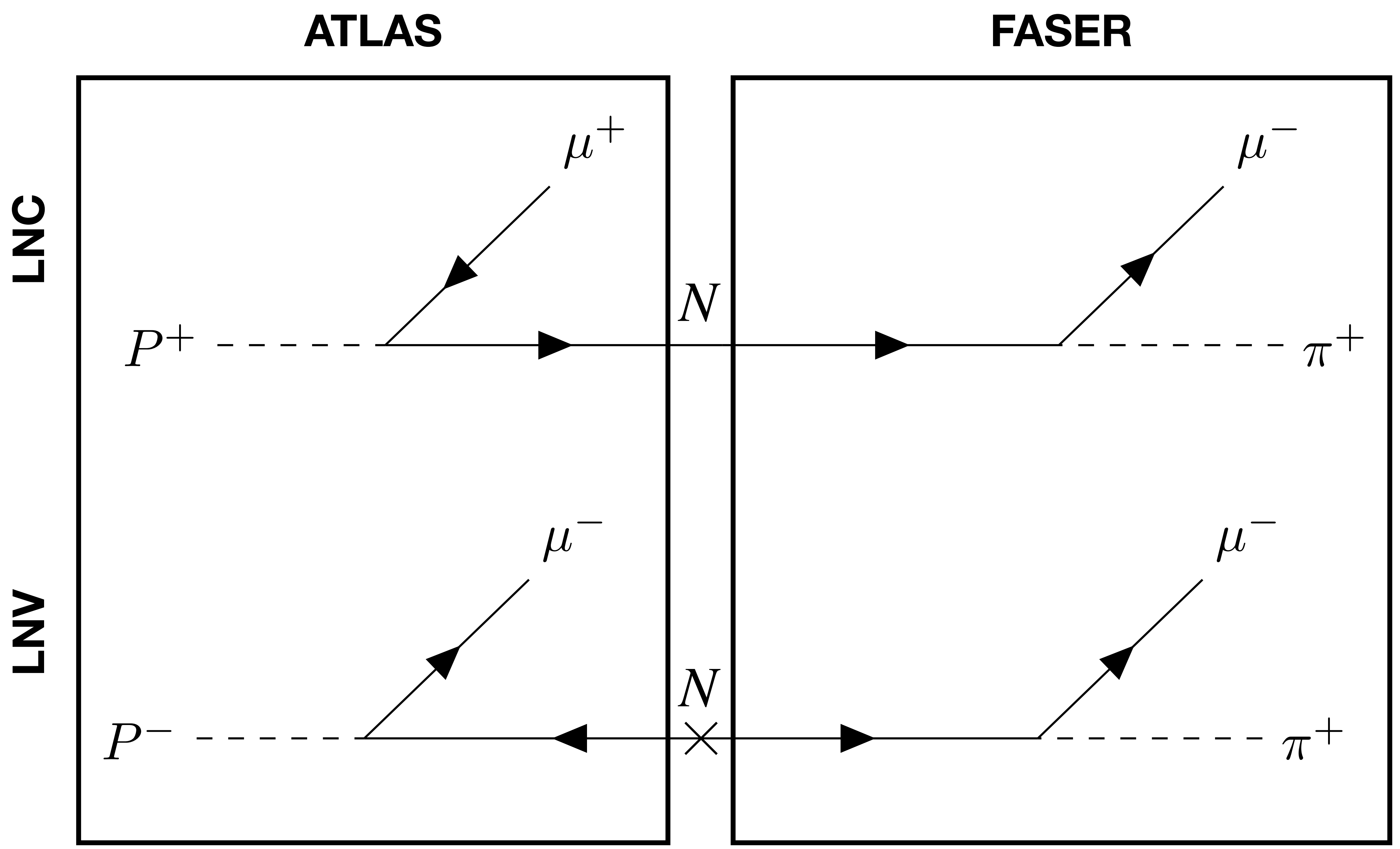




Application:
Lepton-number violation at FASER

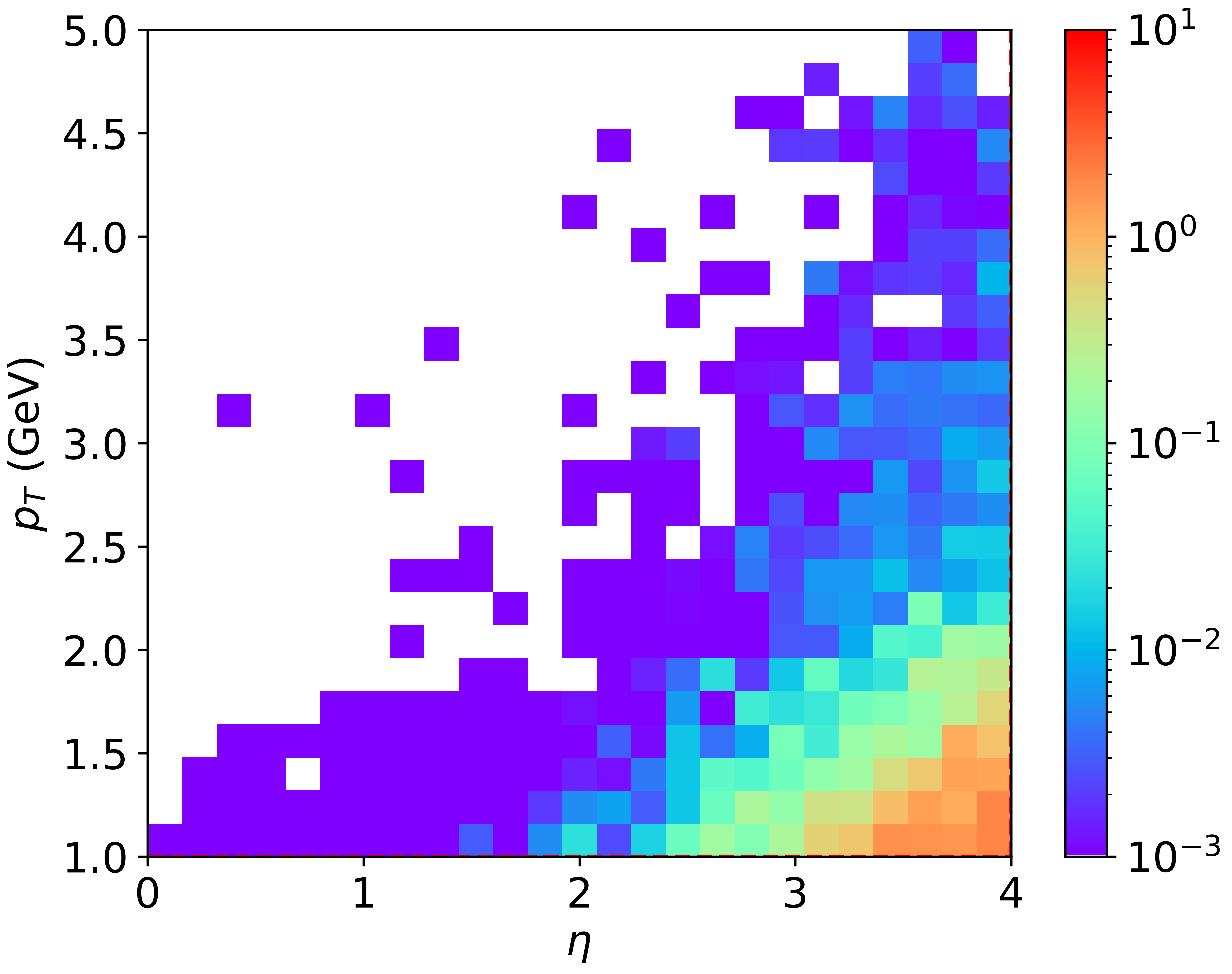
FASER2 as a Trigger for ATLAS

- If an HNL is discovered at FASER, there is currently no mechanism for determining whether that HNL is a Majorana or Dirac particle
  - Determining this would also imply whether active neutrinos are Dirac or Majorana
- If we could Charge ID the lepton produced at ATLAS, we can determine if the whole process was lepton-number-conserving (LNC) or lepton-number-violating (LNV)
- Since these leptons are low p_T (forward boosted), they won't pass ATLAS triggers, therefore we propose to use FASER2 as a trigger for ATLAS
  - Proposed Triggering Time: $5.4\,\mu$s
  - ATLAS Buffer: $6\,\mu$s



FASER2 as a Trigger : Preliminary Results

- Utilizing the FORESEE HNL module, we find that the ATLAS (HL-LHC) inner tracker could see $\mathcal{O}(10)$ events in unconstrained HNL parameter space up to $\eta < 4$ on an event-by-event basis
- The ATLAS inner tracker is proposed to extend existing tracking coverage from $\eta < 2.5$ to $\eta < 4$ for the HL-LHC upgrade (Gonella et al. DOI: 10.1016/j.nima.2022.167597)
- Future Work:
  - Better understanding the background from low-pT charged tracks in the pile-up
  - Investigating whether charge asymmetry in hadron production at FASER could allow for statistical determination of LNV (see Berryman, Gouvêa, Fox, Kayser, Kelly, Raaf 1912.07622 and their work w/ DUNE)



Parameters

$|U_\mu| = 0.002 \quad m_N = 1.8$ GeV $\quad \mathscr{L} = 3$ ab^{-1}

Summary

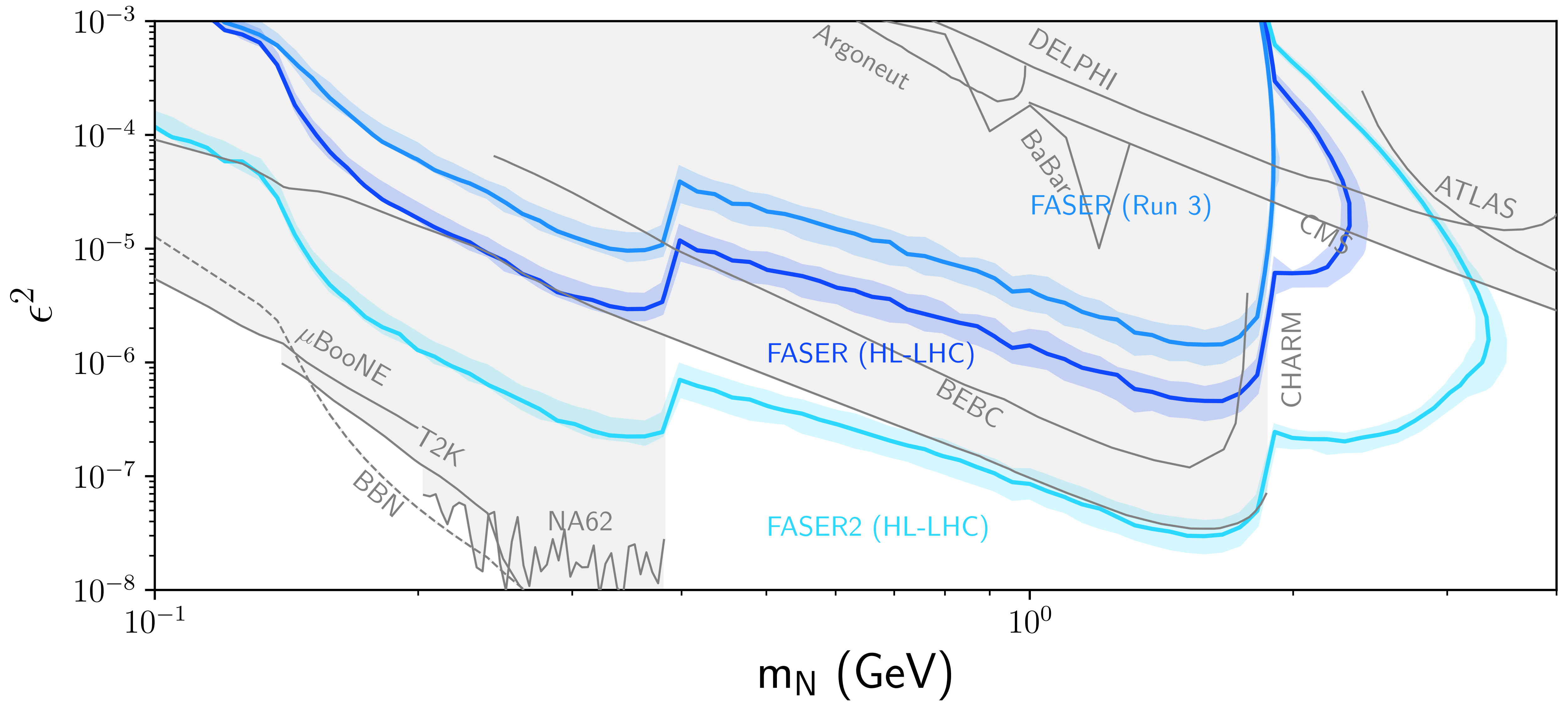
- Heavy Neutral Leptons are a simple, well-motivated extension to the SM which have a rich phenomenology to be studied at colliders
- We have presented HNLCalc - a fast, flexible, and comprehensive python package for calculating HNL production and decay rates with arbitrary couplings to active neutrino flavors
- As an application of this package, we have extended the FORESEE model library to include HNLs, allowing for the study of HNL phenomenology at forward physics experiments
- Using FORESEE, we presented the physics reach for FASER/FASER2 in the $U_e = U_\mu = U_\tau \neq 0$ benchmark, where we find the potential to probe previously unconstrained parameter space
- Lastly, we present preliminary work suggesting that FASER could be used as a trigger for ATLAS, allowing for the determination of the Majorana or Dirac nature of neutrinos on an event-by-event basis and the possibility of observing the entire lifetime of an HNL, from production to decay.

Backup Slides

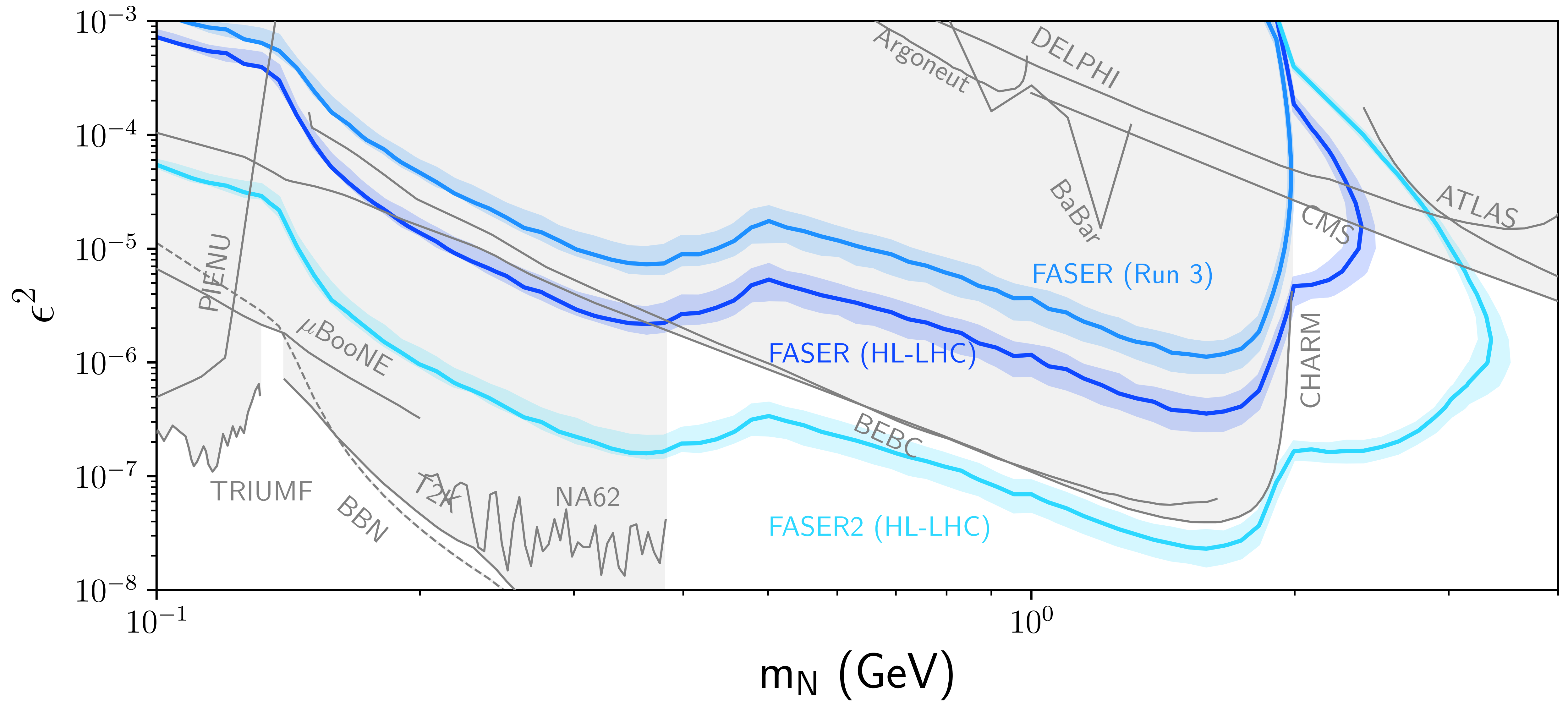
FASER Sensitivity:
Singly Coupled Benchmarks

FASER Sensitivity:
Mixed Coupling Benchmarks

$U_\mu = U_\tau \neq 0,\ U_e = 0$



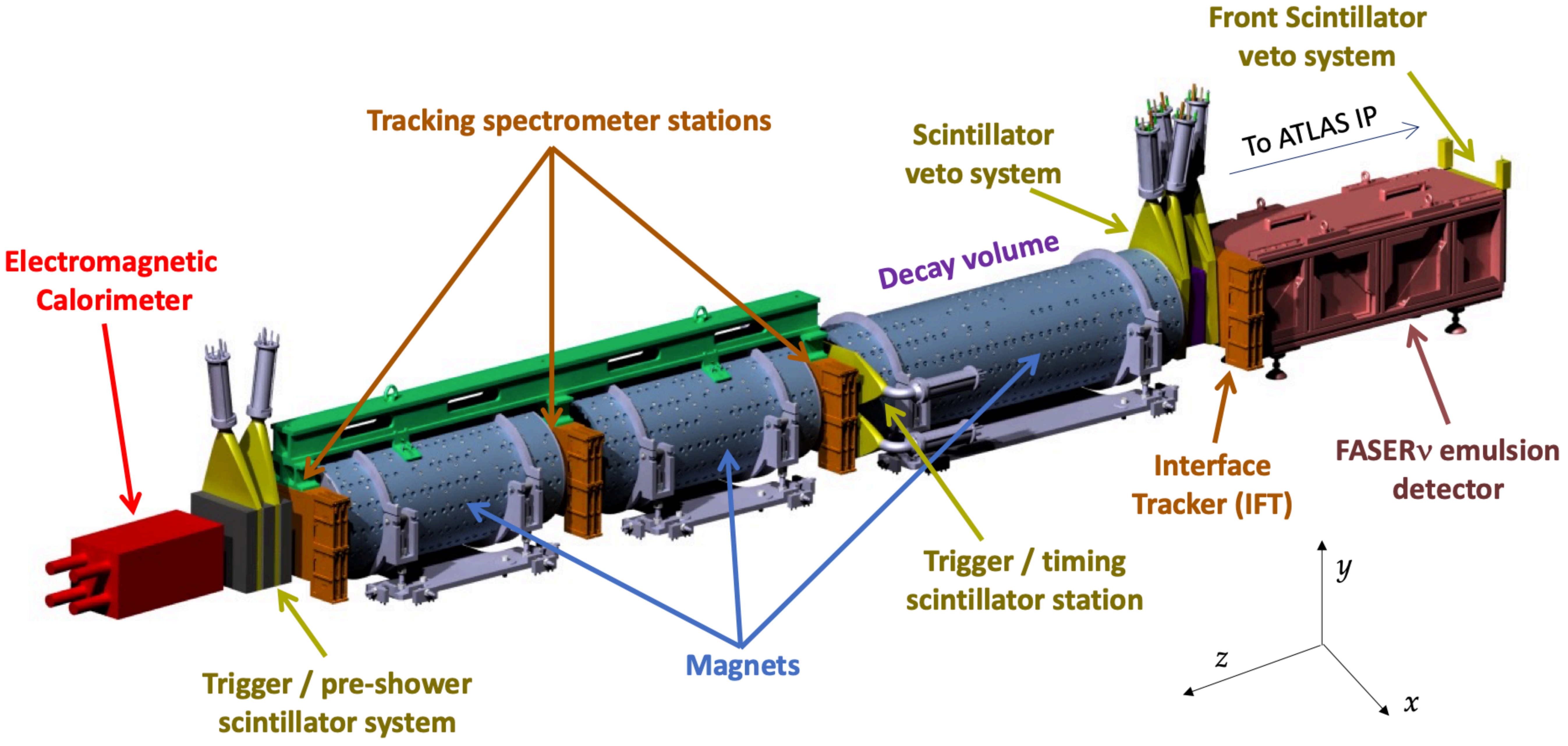
$U_e = U_\mu = U_\tau \neq 0$



Detector Configurations

- The ForwArd Search ExpeRiment (FASER) is an experiment at the LHC designed to detect forward boosted LLPs produced at the ATLAS interaction point
- Located 480 meters down the beam axis, through 100m of rock
- FASER2 is a proposed Forward Physics Facility (FPF) experiment with an enlarged decay volume, which could extend the physics reach of the FASER program significantly

	L	Δ	Geometry	$\mathcal{L}$
FASER (Run 3)	480 m	1.5 m	Cyl. $R = 10\,\text{cm}$	$250\,\text{fb}^{-1}$
FASER (HL-LHC)	480 m	1.5 m	Cyl. $R = 10\,\text{cm}$	$3\,\text{ab}^{-1}$
FASER2 (HL-LHC)	650 m	10 m	Rect. $3\,\text{m} \times 1\,\text{m}$	$3\,\text{ab}^{-1}$



[FASER Collaboration 2207.11427]